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ROLE OF ELECTRICAL PROPERTIES IN AIRBORNE AND SATELLITE BORNE SENSING

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ABSTRACT

The sensitivity of airborne and satellite borne electromagnetic surveys depends on the changes in the electrical properties of earth. These electrical properties vary significantly with various physical parameters in the extended frequency of electromagnetic signals. In the present paper, the effectiveness of electrical properties in the airborne and satellite borne electromagnetic surveys have been discussed.

INTRODUCTION

The quantitative and qualitative interpretation of airborne and satellite borne electromagnetic data depend upon the accurate knowledge of the electrical properties of the underlying geologic materials and conversely the electrical properties (conductivity and dielectric constant) of the geologic materials govern the electromagnetic response measured by the airborne and satellite borne surveys. The electromagnetic wave response is differential in the extended frequency range. The low frequency electromagnetic response is controlled by conductivity, whereas, dielectric constant controls the high frequency electromagnetic response /1/. The conductivity of the geologic materials have been widely studied and therefore the quantitative and qualitative interpretation of low frequency electromagnetic data are relatively well established and developed. The dielectric properties of the geologic materials are also extensively studied in low frequency range /2-3/ , whereas at high frequencies, the dielectric studies are comparatively meagre. This status needs to be improved because most of the airborne and satellite borne electromagnetic sensing studies of the earth's surface are carried out at high frequencies. The importance of the electrical properties of earth's materials at high frequencies can be best shown through the detailed sensitivity analysis. The applications of sensitivity functions in various areas of geophysical problems have been studied by a large number of workers. Parker /4/ presented analytical solutions for one-dimensional electromagnetic induction problems and showed that the magnetotelluric response is Frechet differentiable with respect to conductivity. Oldenburg /5/ derived the Frechet kernels using standard perturbation approach for one-dimensional natural source magnetotelluric observations. The concept of sensitivity functions has been applied by Gomez-Trevino and Edwards /6/ to illustrate the complementary nature of direct current resistivity and electromagnetic induction methods. Similar applications have been given by Chave /7/ and by Edwards et al. /8/ in relation with the electrical soundings on sea floor. The Frechet differentiability of one-dimensional magnetotelluric response function and the associated electric fields have been derived by MacBain /9,10/. Gomez-Trevino /11/ studied the behavior of sensitivity functions using Frechet derivatives over a homogeneous earth, and discussed its main features in both frequency and time domains. Gomez-Trevino /12/ studied the non-linear integral equations for electromagnetic inverse problems and showed that the dependence of the electric and magnetic fields on conductivity distribution within the earth can be expressed as a simple weighted average of conductivity distribution. Neglecting the geometry of the source-receiver configuration, Boerner and West /13,14/, examined the two fundamental response kernels (injected and induced) comprising of electromagnetic fields in a layered earth, and illustrated the frequency characteristics and spatial variations of the electromagnetic fields reflected from various layers of the stratified earth. McGillivary and Oldenburg /15/, have put forward three different techniques to obtain Frechet derivatives and their sensitivities for non-linear inverse problems, and have also illustrated the application of these techniques to 1-D and 2-D resistivity problems.

The understanding of the dependence of sensitivity functions on various parameters is important in understanding the physics of airborne and satellite borne electromagnetic measurements. With a view to fill-up some gaps, in this paper we discuss the role of geologic materials in studying the behavior of sensitivity of airborne and satellite borne electromagnetic measurements.

THEORY

The electromagnetic wave equations for an isotropic homogeneous medium $e^{i\omega t}$ is written as

$$\nabla^2 \vec{E} = (i\,\omega\mu_o\sigma - \omega^2\,\mu_o\,\varepsilon)\vec{E}$$

$$\text{and} \qquad \nabla^2 \vec{H} = (i\,\omega\,\mu_o\sigma - \omega^2\,\mu_o\,\varepsilon)\vec{H} \qquad (1)$$

where σ, μ_o, ε and ω are conductivity, permeability, dielectric capacitivity and angular frequency respectively. The factor multiplying the electric and magnetic fields in equation (1) is known as propagation constant (γ) which is written as

$$\gamma = (i\,\omega\,\mu_o\sigma - \omega^2\,\mu_o\,\varepsilon_r')^{1/2}$$

$$= \omega\mu_o^{1/2}\,\varepsilon_o^{1/2}(-\varepsilon/\varepsilon_o + i\,\sigma/\omega\,\varepsilon_o)^{1/2}$$

$$= \omega/c(-\varepsilon_r' + i\,\varepsilon_r'')^{1/2}$$

$$= \omega/c(\varepsilon_c^*)^{1/2}$$

where $c = (1/\mu_o\varepsilon_o)^{1/2}$ is the velocity of electromagnetic wave propagation in free space, μ_o is the permeability of free space and ε_c^* is the complex dielectric constant which is decomposed and written as

$$\varepsilon_c^*(\omega) = -\varepsilon_r'(\omega) + i\,\varepsilon_r''(\omega)$$

where $\varepsilon_r'(\omega)$ is the real dielectric constant and $\varepsilon_r''(\omega)$ is the imaginary part of dielectric loss factor. The ratio of the imaginary part of dielectric constant to the real dielectric constant is defined as "loss tangent" and written as

$$\tan\delta = \varepsilon_r''(\omega)/\varepsilon_r'(\omega)$$

The dielectric constant and loss tangent two together for any material are known as "dielectric properties" and have been used extensively as a powerful diagnostic tool /1/.

The dielectric properties of subsurface material are also controlled by surface texture, density, porosity and water content. Several investigators /2,16/, have observed that at low frequencies, the dielectric constant is approximately inversely proportional to frequency and levels off at higher frequencies at about 10^7 Hz. The cause of the inverse dependence on frequency is not well known. Chew /3/ has just stated that the inverse relation of dielectric constant with the frequency may be due to geometrical or textural effects of rock grains, and interfacial or electrochemical effects due to presence of clay. His conclusion on the dielectric constant of water bearing rocks and their dependence on frequency through salinity is confirmation of many well known results. However this salinity effect is found to diminish at higher frequencies /17,18/. Campbell and Ulrich /19/ have concluded that dry materials have no measurable dispersion at microwave frequencies. Nelson et al. /20/ have reported that the dielectric loss factor $\varepsilon_r''(\omega)$ for most minerals decreases with increase in frequency.

MICROWAVE REMOTE SENSING

Microwave remote sensing utilizes the electromagnetic frequency band. Microwave active and passive sensors are operated in this range and are used extensively as remote sensing tools for a wide variety of applications. Microwave remote sensing has been recognized as an important tool for monitoring the atmosphere and surfaces of planetary objects, snow and ocean surfaces. The active sensors are those that utilize its own source of illumination and measure the reflected energy from the surfaces. Different types of active microwave sensors are radars and scatterometers. Passive sensors are known as microwave radiometers operating in microwave frequency range.

In case of active sensors, the measured quantity is known as scattering coefficient (σ^o), which varies with the dielectric properties of the material as /1/

$$\sigma^o \propto |R|^2 \qquad (2)$$

where $$R = \frac{(\sqrt{\varepsilon_c(\omega)} - 1)}{(\sqrt{\varepsilon_c(\omega)} + 1)}$$

Passive microwave radiometers measure the intensity of the radiation emitted by the scene under observation and is known as brightness temperature (T_B). This brightness temperature depends on the emissivity (e) of the materials and is given by

$$T_B = eT_o + (1-e)T_{bs}$$

where T_o is the physical temperature of the material under observation and T_{bs} denotes the microwave brightness temperature of the sky. The emissivity of any material media is written as

$$e = 1 - |R|^2$$

and varies between 0 for perfectly non emitting material and 1 for perfectly emitting bodies, R is the reflection coefficient and is related to the dielectric properties of the material as shown in equation (2).

SENSITIVITY ANALYSIS AT MICROWAVE FREQUENCIES

The sensitivity of microwave measurements arising from small local changes in the model parameters (dielectric constant) can be derived using Frechet derivatives. We now consider a vertically homogeneous half-space whose relative dielectric constant as a function of depth is represented by $\varepsilon(z)$. The depth axis points downwards, with the origin located on the surface of the half-space. For homogeneous and isotropic media, the impedance on the surface of the earth is given by

$$Z(\omega) = i\,\omega\mu_o/\gamma = i\,\omega\mu_o(i\omega\mu_o\sigma - \omega^2\mu_o\varepsilon_o\varepsilon_r)^{-1/2}$$

where ε_o is the permittivity of free space and ε_r is the relative dielectric constant of the medium, and $\varepsilon = \varepsilon_o\,\varepsilon_r$. In case of dielectric media, since $\omega\,\mu_o\sigma \ll \omega^2\,\mu_o\varepsilon_o\varepsilon_r$, we have

$$Z(\omega) = i\omega\,\mu_o(-\,\omega^2\,\mu_o\,\varepsilon_o\,\varepsilon_r)^{-1/2}$$

$$Z(\omega) = \sqrt{\mu_o/\varepsilon_o\varepsilon_r}$$

which implies $\varepsilon_r(\omega) = (\mu_o/\varepsilon_o).Z^{-2}(\omega)$.

A small change in $\varepsilon_r(\omega)$ is related to a small change in $Z(\omega)$, through the equation

$$\delta\varepsilon_r(\omega) = -2(\mu_o/\varepsilon_o).Z^{-3}(\omega)\,.\,\delta\,Z(\omega) \tag{3}$$

Using the concept of Oldenburg /5/, we can write

$$\delta Z(\omega) = -\int_o^\infty [E_x(z,\omega)/H_y(0,\omega)]^2\,\delta\sigma(z)dz \tag{4}$$

where $E_x(z,\omega)/H_y(0,\omega)$ for a homogeneous half-space is given by

$$E_x(z,\omega)/H_y(0,\omega) = (i\,\omega\mu_o/\gamma).\exp(-\,\gamma z)$$

Substituting (4) in (3) we get the corresponding change in dielectric constant as

$$\delta\varepsilon_r(\omega) = \int_o^\infty 2.(\omega\mu_o).Z^{-3}(\omega).[E_x(z,\omega)/H_y(0,\omega)]^2\;\delta\varepsilon_r''(z)dz \tag{5}$$

where $\sigma(z) = \omega\varepsilon_o\varepsilon_r''(z)$. The factor multiplying $\delta\varepsilon_r''(z)$ in equation (5) is known as Frechet derivative or sensitivity function $G_f(z,\omega)$.

RESULTS AND DISCUSSION

The role of electrical properties (dielectric constant and conductivity) of the earth on the airborne and satellite borne electromagnetic measurements can be studied using Frechet derivatives. Frechet derivatives have been computed for the study of sensitivity analysis over homogeneous half space at frequencies 10^7 and 10^9 Hz using equation (5). In Figures 1-4, we have shown the variation of real and imaginary parts of sensitivity functions at 10^7 and 10^9 Hz for earth models using conductivity 10^{-2} and 10^{-3} mhos/m and dielectric constant 4 and 9 with varying depth. The sensitivity functions show oscillations with the increase of depth. The magnitude of sensitivity functions changes

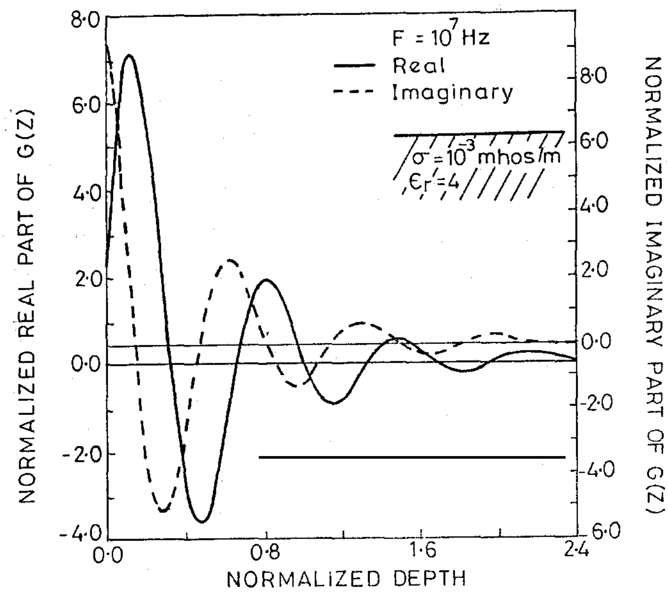

Fig. 1. Variation of sensitivity functions with depth for frequency 10^7 Hz.

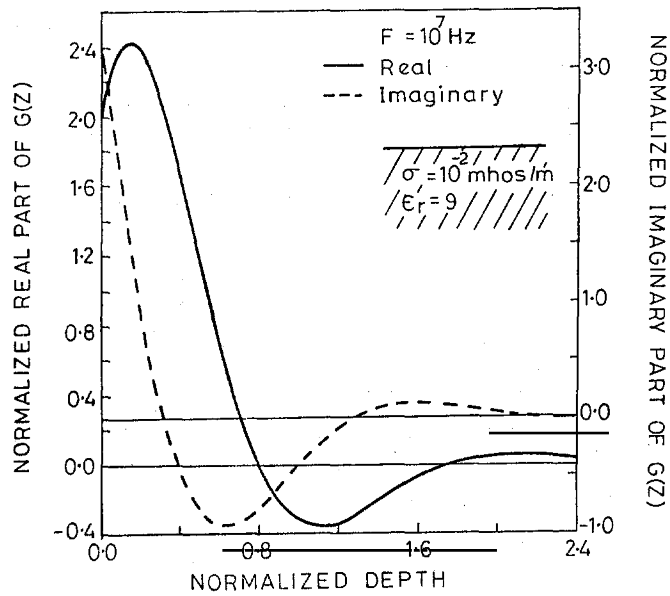

Fig. 2. Variation of sensitivity functions with depth for frequency 10^7 Hz.

with the change in electrical properties of the earth. The effect of frequency is also found to be significant with the change in frequencies (Figures 1-4). It has also been found from the theoretical analysis that the magnitude of the sensitivity function increases with the increase in the dielectric constant when there is no change in the conductivity of the earth. This is because at high frequencies, the equivalent or effective conductivity (σ') of the earth combines with the true ohmic conductivity (σ) with the dielectric hysteresis [$\omega\epsilon_r''(\omega)$] and results in more reflected energy. Similar behavior has also been observed in case of increase in conductivity when the dielectric constant is kept unchanged. From Figures 1-4, it is found that the electrical properties of the earth control the sensitivity of measurements at 10^7 and 10^9 Hz frequencies which are generally used in the airborne and satellite borne electromagnetic measurements.

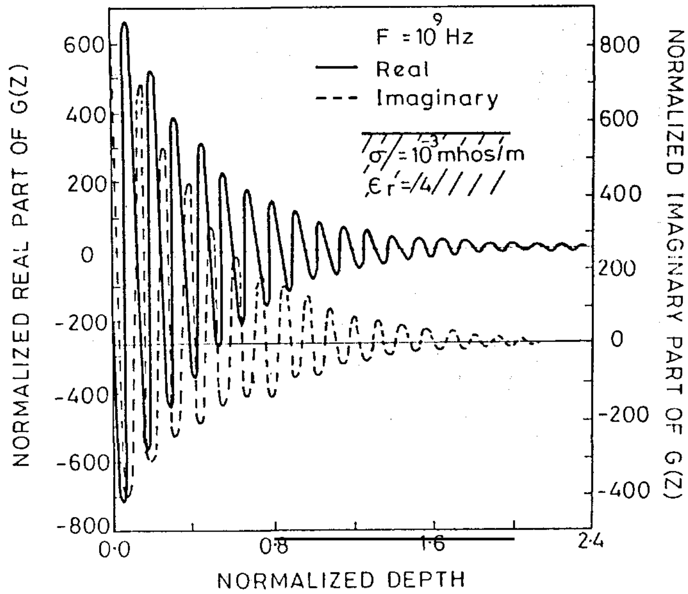

Fig. 3. Variation of sensitivity functions with depth for frequency 10^9 Hz.

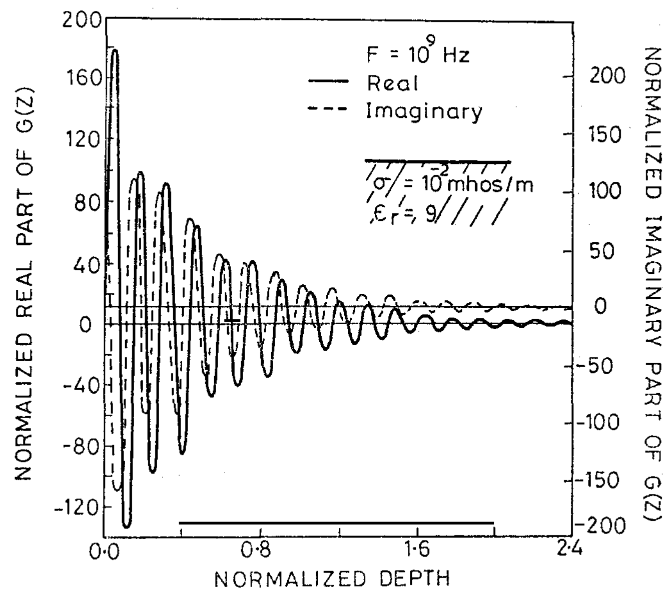

Fig. 4. Variation of sensitivity functions with depth for frequency 10^9 Hz.

CONCLUSIONS

Numerical computations have been made for the study of role of electrical properties of stratified earth's surface at microwave frequencies through sensitivity analysis. The computed results show a characteristic dependence of sensitivity functions for the stratified models used. Such type of studies comparatively more useful to investigate the areas containing a mixture of dry sand, frozen ground or rocks with low water content and moist rocks. This computational technique is comparatively more powerful than the usual response evaluation technique.

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